

PATENT APPLICATION

Docket No.: D498

Inventor(s): Karl W. Baker

Title: Superheater Capillary Two-Phase Thermodynamic  
Power Conversion Cycle System

SPECIFICATION

Statement of Government Interest

The invention was made with Government support under  
contract No. F04701-00-C-0009 by the Department of the Air  
Force. The Government has certain rights in the invention.

Reference to Related Application

The present application is related to applicant's  
copending application entitled Capillary Two-Phase  
Thermodynamic Power Conversion Cycle System S/N: xx/xxx,xxx,  
filed yy/yy/yy, by the same inventor, here incorporated by  
reference as there fully set forth.

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Field of the Invention

The invention relates to the field of thermodynamic power systems. More particularly, the present invention relates to two-phase thermal cycle systems, capillary devices, power generators, thermal condensers and liquid pumps.

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## Background of the Invention

Thermodynamic power cycle systems have typically been used to generate useful work, such as in power generation systems. Thermodynamic power cycles have typically been used to turn heat input into the system into useful work as for power generation. Radioisotope elements, active nuclear and solar are used as heat sources for space power systems. Thermoelectric power conversion systems are currently used in deep space missions while photovoltaics are used for earth orbiting and some planetary missions. Radioisotope thermoelectric generators have thermodynamic efficiencies of seven to four percent or less while photovoltaics have overall efficiencies of typically 16% at end of life.

It is desirable to increase the efficiencies and power conversion levels of space based power generators. It is also desirable to directly produce AC power and thus eliminate the need for power converters for certain applications. It is also desirable to achieve high efficiencies and power conversion levels while the power conversion system operates at a lower maximum temperature relative to other power conversion systems. It is also desirable to have a power cycle that accepts heat input at different temperature levels. These different heat input temperatures allow for the recovery of waste heat used as heat input. It is also advantageous to have a power conversion system that is capable of storing energy using thermal energy storage media that is more efficient than batteries. It is also

1 desirable to have a power system capable of operating as a  
2 bottoming cycle in a space-based cogeneration power system.  
3 Space power systems that do not generate AC power  
4 disadvantageously may require the use of an additional power  
5 converter, such as in photovoltaic and thermoelectric systems.  
6 Turbines have been used both terrestrially and in space to  
7 generate AC power. Space based dynamic power conversion cycles  
8 have been limited to single-phase Brayton and Stirling systems.  
9 The overall thermodynamic efficiency of two-phase power  
10 conversion systems, such as the Rankine system, is generally  
11 greater than single-phase systems. Large terrestrial two-phase  
12 Rankine cycle systems typically operate at over thirty percent  
13 efficiency. Although the Rankine cycle has been used  
14 extensively in terrestrial applications for power generation,  
15 the Rankine power cycle has not been used in space applications  
16 because of the difficulty and complexity required to manage a  
17 two-phase power system fluid in micro gravity.

18  
19 Rankine cycle systems are typically described using  
20 conventional temperature and entropy graphs and functional  
21 block descriptions. A typical Rankine system includes an input  
22 heat source, a boiler, a superheater, a turbine, a condenser,  
23 and a liquid pump. Heat is input into the boiler, the working  
24 fluid gradually changes from liquid to vapor as heat is  
25 received. That is, the Rankine cycle entropy extends from a  
26 subcooled liquid point to a saturated vapor point during heat  
27 addition. The heating in the boiler of a Rankine cycle system  
28 provides the working fluid flow with an infinitesimally small

1 amount of heat input, which results in an infinitesimally small  
2 change in the quality of the flow. In the boiler of a Rankine  
3 cycle system, the vapor and liquid are carried together. The  
4 boiler provides a phase change from liquid to vapor. The input  
5 heat source heats the working fluid in the boiler generating  
6 and providing saturated vapor, which is fed into the  
7 superheater. The superheated vapor then spins the turbine for  
8 providing output work, such as electrical power. The  
9 superheater is used to ensure that the vapor entering the  
10 turbine is superheated to a higher pressure and thus has no  
11 liquid droplets in it to avoid liquid impingement with the  
12 turbine blades while providing sufficient pressure and flow to  
13 spin the turbine to generate the desired amounts of power. The  
14 turbine provides low-pressure saturated vapor to the condenser.  
15 The condenser provides a phase change from vapor to liquid. The  
16 liquid is then pumped by the active pump into the boiler for  
17 completing the cycle. The Rankine cycle disadvantageously  
18 requires all input heat to be transferred to the work fluid  
19 while at one pressure. Having the working fluid at constant  
20 pressure during the heat addition process restricts the cycle  
21 and limits the amount of low temperature heat that can be  
22 added. Rankine cycle also disadvantageously uses a boiler to  
23 add heat to the cycle flow. For terrestrial applications,  
24 gravity is used to maintain the separation of liquid and vapor  
25 in the boiler and at the active liquid pump. Maintaining this  
26 separation without gravity, in space, is difficult and  
27 typically makes Rankine power cycle systems unsuitable for  
28 space applications.

1  
2 Commercial loop heat pipes and capillary pumped loops have  
3 been developed to passiv ly control the dynamics and location  
4 of liquid and vapor interface points in micro gravity. As such,  
5 loop heat pipes and capillary pumped loops are commonly used  
6 for the thermal control of spacecraft. To date, there are over  
7 one hundred loop heat pipes and capillary pumped loops in  
8 operation, on orbit, on spacecraft. The loop heat pipe as well  
9 as the capillary pumped loop allows deployable condensers to be  
10 used on spacecraft as part of a two-phase heat rejection  
11 system. A loop heat pipe or capillary pumped loop includes a  
12 capillary wick that facilitates flow from a low pressure point  
13 to a high pressure point. The capillary wick is used to  
14 pressurize and drive the loop heat pipe or capillary pumped  
15 loop heat rejection system. Loop heat pipes and capillary  
16 pumped loops have pumping capabilities orders of magnitude  
17 greater than simple heat pipes. Loop heat pipes are being used  
18 on commercial satellites and are described in U.S. Patent  
19 5,743,325. The transport lines of the loop heat pipe or a  
20 capillary pumped loop heat rejection system are typically made  
21 from simple tubing that is bent and welded. Loop heat pipe and  
22 capillary pumped loop systems use Aluminum, stainless steel and  
23 other nickel based superalloys for use typically with ammonia  
24 as the working fluid. Deployable condensers and flexible tubing  
25 are used to configure the heat rejection system.

1       A capillary wick receives a saturated liquid. The liquid  
2 wets the capillary wick. It is drawn through the capillary wick  
3 because the working fluid molecules are attracted more to the  
4 capillary wick material than they are to each other. The liquid  
5 is also pushed through the capillary wick through  
6 pressurization. The capillary wick provides the separation  
7 between the high-pressure vapor and the low-pressure liquid.  
8 Heat is input on the high-pressure side of the capillary wick  
9 where the fluid is vaporized. Once liquid turns into vapor  
10 through evaporation, the volume of the working fluid increases  
11 orders of magnitude causing the pressure to increase on the  
12 high-pressure side of the capillary wick. This increase in  
13 pressure pushes the saturated vapor forward through the system.  
14 The flow cannot go backwards toward the lower pressure  
15 saturated liquid path because the pores in the capillary wick  
16 are so small that a meniscus forms in them and acts as a  
17 barrier to the high-pressure vapor. Capillary wicks with pores  
18 sizes of about one micron are commercially available. Based on  
19 the Laplace-Young equation, which is a function of pore  
20 geometry and surface tension, and wetting angle and using  
21 ammonia as a working fluid, a capillary wick with one-micron  
22 pores can sustain a pressure differential of approximately ten  
23 psi.

24  
25       The loop heat pipe is similar to a capillary pumped loop,  
26 but having different placement of the fluid reservoir. In the  
27 loop heat pipe, the reservoir is attached to the evaporator. In  
28 the capillary pumped loop, the reservoir is remotely located

1 with respect to the evaporator. A loop heat pip or capillary  
2 pumped loop generates fluid pumping n rgy through the addition  
3 of heat, from an input heat source, onto a capillary wick.

4  
5 Two-phase power systems are the most efficient types of  
6 power systems. The two-phase liquid vapor interface management  
7 problem is solved for loop heat pipe and capillary pumped loop  
8 thermal control capillary devices. Although two-phase systems  
9 have been used extensively on earth, two-phase power systems  
10 have not been used in space because of an inability for  
11 controlling the interface between the two-phases in micro  
12 gravity during steady state operation as well as transient  
13 operation. These and other disadvantages are solved or reduced  
14 using the invention.

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## Summary of the Invention

An object of the invention is to provide a two-phase thermal cycle for use as a thermodynamic power system pressurized by a capillary device, superheater and liquid pump.

Another object of the invention is to provide a two-phase thermal cycle for use in a thermodynamic power system pressurized by a capillary device, superheater and liquid pump for driving a turbine for providing output energy.

Yet, another object of the invention is to provide a two-phase thermal cycle for use in a thermodynamic power system pressurized by a capillary device, superheater and liquid pump for generating power during power generation.

Yet, another object of the invention is to provide a two-phase thermal cycle for use in a thermodynamic power system pressurized by a capillary device, superheater and liquid pump for generating power at high efficiencies while operating at low temperatures.

Yet, another object of the invention is to provide a two-phase thermal cycle for use in a thermodynamic power system pressurized by a capillary device, superheater and liquid pump for generating power using heat input at varying pressures and temperatures.

1        Yet another object of the invention is to provide a two-  
2 phase thermal cycle for use in a thermodynamic power system  
3 pressurized by a capillary device, superheater and liquid pump  
4 for generating power using low grade or waste heat for recovery  
5 as part of the total heat input.

6  
7        Yet another object of the invention is to provide a two-  
8 phase thermal cycle for use in a thermodynamic power system  
9 pressurized by a capillary device, superheater and liquid pump  
10 for generating power from a nonsteady heat source operating  
11 using stored thermal energy.

12  
13        Yet another object of the invention is to provide a two-  
14 phase thermal cycle for use in a thermodynamic power system  
15 pressurized by a capillary device, superheater and liquid pump  
16 for generating power as a bottoming cycle in a cogeneration  
17 power system.

18  
19        A further object of the invention is to provide a two-  
20 phase thermal cycle for use in a thermodynamic power system  
21 pressurized by a capillary device, such as a loop heat pipe,  
22 superheater and liquid pump.

23  
24        Yet, a further object of the invention is to provide a  
25 two-phase thermal cycle for use in a thermodynamic power system  
26 pressurized by a capillary device, such as a capillary pumped  
27 loop, superheater and liquid pump.

1 Another object of the invention is to provide a two-phase  
2 thermal cycle for use in a thermodynamic power system  
3 pressurized by a capillary device providing an instantaneous  
4 transition from liquid to vapor phase of the working fluid  
5 using input heat.

6  
7 Still a further object of the invention is to provide a  
8 two-phase thermal cycle for use in a thermodynamic power system  
9 pressurized by a capillary device for generating power during  
10 power generation with improved efficiency using an in-line  
11 superheater, a preheater, and a liquid pump.

12  
13 The system is directed to a two-phase thermodynamic power  
14 cycle system that converts heat energy to work particularly  
15 useful in space power systems. The system uses a capillary wick  
16 of a capillary device that uses input heat to generate high-  
17 pressure saturated vapor. The high-pressure saturated vapor is  
18 kept separate from low-pressure saturated liquid. This  
19 capillary wick facilitates the flow transition from high  
20 pressure, high temperature, saturated liquid to high-pressure,  
21 saturated vapor, instantaneously, providing effective  
22 separation between liquid and vapor and being a passive pump.  
23 The system solves the problem of two-phase fluid management in  
24 micro gravity by simplifying the two-phase thermodynamic cycle  
25 system using a capillary device, such as loop heat pipe or a  
26 capillary pumped loop, for two-phase fluid control. The system  
27 is a power conversion unit that receives heat from a heat  
28 source to passively drive the capillary action. The capillary

1 action passively separates liquid from vapor and pressurizes  
2 the flow so that high-pressure saturated vapor can enter the  
3 superheater of the system. Saturated high-pressure vapor flows  
4 into the superheater through diode valves. These valves allow  
5 the flow to enter the superheater but prevent the flow from  
6 flowing back towards the evaporator. Once the pressure in the  
7 superheater equals the pressure of the high pressure, saturated  
8 vapor, flow into the superheater stops. Heat addition to the  
9 high-pressure, saturated vapor continues until the vapor  
10 reaches the desired superheated vapor state. Once the vapor  
11 reached the desired state of superheat, the superheater control  
12 valve is opened releasing superheated vapor that flows to the  
13 turbine. Vapor flows isentropically through the turbine where  
14 work is taken out of the flow. Multiple superheater stages can  
15 be used. The pulsing of these multiple stages can be staggered  
16 in order to obtain a flow that is steadier than simple pulses.  
17 The superheater can be one leg or several parallel tube legs,  
18 for example each leg tens of feet long, bent in a serpentine  
19 manner, attached to a heat source. Each leg of the superheater  
20 has a controllable diode input valve and controllable exit  
21 valve. The flow exits the turbine as low-pressure, saturated  
22 vapor and enters the condenser. The vapor condenses in the  
23 condenser and leaves as low pressure saturated liquid. The  
24 condenser can be one tube, for example, tens of feet long, bent  
25 in a serpentine manner, and attached to a condenser panel. The  
26 condenser tubing can also be fabricated in a conventional  
27 parallel arrangement. Liquid enters a pump where work is put  
28 in and the liquid is pressurized isentropically to a high

1 pressure, low temperature, subcooled liquid. The high pressure,  
2 low temperature, subcooled liquid flows through the liquid  
3 preheater and leaves as a high pressure, high temperature,  
4 saturated liquid which enters the evaporator to repeat the  
5 cycle. The liquid preheater can be one tube, for example, tens  
6 of feet long, bent in a serpentine manner, and attached to a  
7 heat source. The preheater tubing can also be fabricated in a  
8 conventional parallel arrangement.

9  
10 The system preferably includes an evaporator comprising a  
11 capillary device having a capillary wick for receiving input  
12 heat and providing a phase change, a vapor accumulator to  
13 dampen and prevent mass flow oscillations from effecting the  
14 operation of the evaporator, a superheater receiving input heat  
15 and providing further increased pressure and temperature to the  
16 high pressure saturated vapor, a turbine for providing power,  
17 a condenser for radiating heat, a liquid pump for increasing  
18 the pressure of the low pressure saturated liquid and a  
19 preheater for increasing the temperature of the high pressure,  
20 low temperature, subcooled liquid.

21  
22 The loop heat pipe or capillary pumped loop, collectively  
23 referred to as capillary devices, are preferably used in  
24 combination with a vapor accumulator, superheater, turbine,  
25 liquid pump and liquid preheater to produce output power. A  
26 turbine can be placed in the thermal cycle loop for providing  
27 output power during power generation. The system includes  
28 necessary tubing for transport of the working fluid between

1 components, through the superheater, condenser, liquid pump and  
2 liquid preheater. The system can be used for small terrestrial  
3 solar, gas, heat recovery and/or geothermal as heat sources for  
4 power generation stations with an efficiency potentially higher  
5 than photovoltaic and basic Rankine systems. High grade AC  
6 power can be generated directly using a turbine-rotating  
7 machine to generate power.

8  
9       The system preferably uses spacecraft thermal control  
10 technology, including loop heat pipes and capillary pumped  
11 loops, by combining these capillary devices with a turbine,  
12 superheater, liquid pump and liquid preheater. Loop heat pipes  
13 and capillary pumped loops are used for thermal control  
14 applications on spacecraft for a variety of reasons including  
15 that these devices allow for system integration with flexible  
16 lines, and enable deployable condensers. The system provides a  
17 two-phase dynamic power system suitable for space application.  
18 The system can be cost efficiently built as a system to  
19 generate power using the waste heat as a portion or all of the  
20 input heat from a spacecraft or waste heat from another dynamic  
21 or static power converters in a cascaded manner. This waste  
22 heat or cascaded system will yield a space power system with an  
23 overall efficiency of well over thirty percent to provide a  
24 spacecraft with significantly more power while enabling ion  
25 propulsion and increased payload capabilities.

26  
27       The system obtains pressurization of high pressure,  
28 saturated vapor flow occurring at the capillary wick. In the

1 thermal cycl of the system, high pressure saturated vapor and  
2 high pressure, high temperature saturat d liquid points are  
3 separated during the capillary heat source input phas of the  
4 cycle. That is, the working fluid abruptly changes from a  
5 saturated high pressure, high temperature saturated liquid to  
6 high-pressure saturated vapor. During heat addition, high  
7 pressure, high temperature, saturated fluid changes directly to  
8 high pressure, saturated vapor and the quality of the flow goes  
9 directly from all liquid to all vapor. The thermal cycle  
10 process jumps from the high pressure, high temperature,  
11 saturated liquid point to high-pressure, saturated vapor point.  
12 This entropy jump on the temperature and entropy diagram  
13 mirrors the physics at the liquid vapor interface of the  
14 capillary wick, where high pressure high temperature saturated  
15 liquid is physically in contact, but separated from high  
16 pressure saturated vapor. When an infinitesimally small amount  
17 of heat is added at the saturated vapor side of the capillary  
18 wick, an infinitesimally small amount of high pressure,  
19 saturated vapor will be formed. At the vapor liquid interface  
20 of the thermal cycle, liquid and vapor are in contact but  
21 separated across the capillary wick. The capillary wick can be  
22 built using different types of materials and in different  
23 geometries. The evaporator of a loop heat pipe or capillary  
24 pumped loop contains a capillary wick. The loop heat pipe  
25 evaporator includes a primary capillary wick and a secondary  
26 wick, the reservoir, the liquid input line, and vapor exit  
27 line, as well as the housing for th primary capillary wick.  
28 The capillary wick receives heat from an input heat source.

1 Conventional loop heat pipe or capillary pumped loop  
2 evaporators can be used.

3  
4 The superheater is used to significantly increase the  
5 pressure of the vapor by adding additional heat bringing it to  
6 a superheated state. Although the vapor flow from the  
7 evaporator flows through the accumulator into the superheater,  
8 the evaporator is not exposed to the high pressures generated  
9 in the superheater. This is accomplished by pulsing the  
10 superheater using controllable diode and control valves. This  
11 allows for significantly higher-pressure, superheated vapor to  
12 flow into the turbine for power generation. This also insures  
13 that the working fluid flowing into the turbine is all vapor.  
14 In the preferred form of the invention, the superheater,  
15 disposed after the capillary wick and accumulator, is connected  
16 to a higher temperature heat source compared to the evaporator  
17 and liquid preheater heat sources. The superheater used in  
18 combination with a preheater and with a liquid pump that are  
19 both disposed before and the capillary wick allow for improved  
20 efficiency by increasing the operating range of the system.  
21 The flow is high-pressure saturated vapor that flows into the  
22 superheater. The superheater is preferably a heat exchanger  
23 that must interface with a heat source that is maintained at a  
24 higher temperature than the capillary wick. In practice, the  
25 superheater is a plurality of heat exchanging tubular chambers  
26 through which the cycle working fluid flows and is heated. Flow  
27 at the entrance to these chambers is checked by a diode valve,  
28 only allowing flow in. The exit to these chambers is checked by



1 a control valve, operated so that the chamber puls s. This heat  
2 chamber can be attached to an external heat sourc . The flow is  
3 then heated for staggered release. Using multiple chambers, a  
4 quasi-continuous superheated vapor flow can be achieved for  
5 driving the turbine. The superheater is used to increase the  
6 efficiency of the cycle and to heat the working fluid to ensure  
7 that no condensed droplets enter the turbine. The impingement  
8 of droplets on the turbine will eventually cause the turbine to  
9 erode. The superheated vapor is passed through the turbine.  
10 Thermal energy storage material such as a phase change material  
11 can be connected to the superheater to store energy so that the  
12 superheater can operate constantly even if the heat source is  
13 not steady such as solar heating in Low Earth Orbit. This  
14 thermal energy storage material can be a single phase metal  
15 such as beryllium, or a two phase such as lithium or a molten  
16 salt that changes phase at the superheater operating  
17 temperature.

18  
19 The superheater is used to increase power output of the  
20 device by adding heat into the flow. The liquid pump is used to  
21 increase the pressure of the condensed liquid so that the  
22 liquid returning to the evaporator is at a pressure close to  
23 that of the high-pressure saturated vapor. Using the  
24 superheater and liquid pump the pressure difference, from  
25 lowest pressure to highest pressure in the cycle can be  
26 increased without regard to the maximum sustainable pressure  
27 differential across th capillary wick. The capillary wick is  
28 isolated from these extreme pressur s and is mainly required to

1 separate liquid and vapor. A small pumping capability is  
2 required only to move the high-pressure saturated vapor through  
3 the vapor accumulator into the superheater. The liquid  
4 preheater is used to reduce the amount of evaporator input  
5 energy required. With a liquid pump incorporated into the power  
6 cycle, low operating temperatures, just above the freezing  
7 point of the working fluid, are possible in the condenser.  
8 After this low pressure, saturated fluid from the condenser  
9 passes through the liquid pump it is significantly subcooled.  
10 If this fluid were returned directly to the evaporator without  
11 passing through the liquid preheater, it would require that a  
12 significant amount of additional heat be added through the  
13 evaporator, beyond that required only for evaporation of the  
14 fluid. Because the geometry of the evaporator is restricted  
15 because of limitations with respect to the capillary structure  
16 and the desire to use LHP and CPL flight hardware, additional  
17 heat input to the evaporator will result in increased  
18 temperature gradients that will reduce the efficiency of the  
19 overall system and could cause operation problems. The  
20 preheater geometry can be designed to effectively accept a  
21 portion of the required input heat transforming the working  
22 fluid from a subcooled state to a saturated state allowing the  
23 evaporator to operate more efficiently. For an isotope or  
24 active nuclear space system, the preheater and superheater can  
25 interface with the same heat source that drives the capillary  
26 wick, however the superheater would receive higher temperature  
27 heat. For satellites, the liquid preheater and evaporator could  
28 be exposed to waste heat from the satellite electronics and the

1 superheater could be heated by solar energy. Heat input to the  
2 superheater can be direct from a heat source or using thermal  
3 energy storage. For a space-based application, the turbine can  
4 have an electromagnetic coupling for eliminating leakage around  
5 shaft seals. The superheated vapor drops in pressure as energy  
6 is extracted. The flow will then enter the condenser where heat  
7 will be transferred out to an external sink in the environment.  
8 In practice, the condenser can be a tube that the cycle flow  
9 passes through with several serpentine bends. This tube is  
10 exposed to a cold heat sink. The cold heat sink will cause the  
11 vapor to condense to liquid as the flow is forced through the  
12 condenser tubes. The flow exits the condenser as saturated  
13 liquid to enter the liquid pump where the pressure is increased  
14 isentropically. High pressure, low temperature, subcooled  
15 liquid leaving the pump enters the liquid preheater where heat  
16 is added. The flow, high pressure, high temperature, saturated  
17 liquid leaves the liquid preheater and enters the capillary  
18 wick to repeat the cycle. The system provides two-phase  
19 thermodynamic operation well suited for space-based  
20 applications. These and other advantages will become more  
21 apparent from the following detailed description of the  
22 preferred embodiment.

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Brief Description of the Drawings

Figure 1 is a block diagram of a superheater power generating thermal cycle system.

Figure 2 is a temperature and entropy graph of a superheater power generating thermal cycle.

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## Detailed Description of th Preferred Embodiment

An embodiment of the invention is described with reference to the figures using reference designations as shown in the Figures. Referring to Figure 1, a two-phase thermodynamic power system includes a capillary device, a superheater, an inline turbine, a condenser, a liquid pump and a liquid preheater for generating output power. The capillary device, such as a loop heat pipe or a capillary pumped loop, is coupled to an accumulator that is coupled to the superheater. The capillary device includes a capillary wick and a container, combined to make an evaporator. The capillary device is driven by a capillary heat source. The capillary device provides high-pressure saturated vapor through a high-pressure vapor path to a preferred vapor accumulator that is in turn connected to the superheater. The superheater includes a plurality of unidirectional diode valves, such as valves A, B, and C, that are respectively connected to a plurality of heating chambers, such as chambers A, B, and C, that are heated by a superheater heat source connected to a splitter for routing heat to the chambers. Each of the heating chambers are in turn respectively connected to control valves, such as control valves A, B, and C, that are controlled by a controller for staggered release of superheated vapor through a superheated vapor path to the inline turbine. The superheater is coupled to the inline turbine for generating output power as power out for operation as an electrical power generator. Th low-pressure saturated vapor enters the superheater where it is superheated for

1 driving the turbine. When passing through the turbine, the  
2 superheated vapor is cooled to low-pressure saturated pressure  
3 vapor that is passed into a low-pressure saturated vapor path  
4 connected to a condenser. Low pressure saturated vapor exiting  
5 the turbine condenses to liquid in the condenser into low-  
6 pressure saturated liquid and flows through a low-pressure  
7 saturated liquid path. This low-pressure saturated liquid may  
8 then be preferably pressurized while passing through a liquid  
9 pump providing high-pressure, low temperature subcooled liquid  
10 into a high-pressure, low temperature subcooled liquid path.  
11 The high-pressure, low-temperature, subcooled liquid is then  
12 heated in a liquid preheater provided high-pressure, high-  
13 temperature saturated liquid to the capillary device completing  
14 the cyclic path around the thermodynamic power system. The  
15 capillary device receives input heat from the capillary heat  
16 source and this heat is used to change the phase of the high-  
17 pressure, high-temperature liquid into high-pressure saturated  
18 vapor. The superheater isolates extremely high-pressure vapor  
19 from the capillary device. The optional liquid pump isolates  
20 extremely low pressure liquid from the capillary device  
21 isolating either or both high and low cycle pressures from the  
22 capillary device that allow the cycle to operate at differences  
23 in pressure far greater than that which the capillary device  
24 can sustain, for providing increased power output over the  
25 power that can be provided by only the capillary device.

26  
27 The system relies on a pressure difference generated  
28 during the evaporation of the working fluid from a capillary

1 wick to create a high-pressure saturated vapor that is then  
2 superheated for driving the turbine. Hence, the maximum power  
3 production is not limited by the maximum capillary pressure  
4 differential that can be sustained across the capillary wick.  
5 The superheater is coupled through the flow of the working  
6 fluid but decoupled with respect to pressure from the capillary  
7 wick using unidirectional vapor valves such as the diode  
8 valves. The capillary wick in the cycle provides the pressure  
9 difference generated across the wick structure that is only  
10 required to establish fluid flow through the accumulator and  
11 into the superheater, while separating liquid from vapor. High  
12 temperature heat energy input to the system preferably enters  
13 through the superheater while low-temperature heat energy input  
14 enters through the liquid preheater and evaporator.

15  
16 In the superheater, the flow-pressure is significantly  
17 increased through heat addition. This heat addition creates a  
18 condition where the maximum pressure differential in the cycle  
19 is the highest pressure out of the superheater minus the lowest  
20 pressure of the low-pressure saturated liquid path. This  
21 maximum pressure differential is far greater than the pressure  
22 differential that the capillary wick can sustain. However, the  
23 capillary wick is not subjected to this maximum pressure  
24 differential because the capillary wick is isolated from the  
25 pressure in the superheater by the diode valves. That is, the  
26 efficiency and power production of the system is not limited to  
27 only the pressure differential that the capillary device can  
28 sustain. High-pressures generated in the superheater do not

1 affect the pressure in the high-pressure saturated vapor path  
2 of the cycle because pressures in the superheater are isolated  
3 from the saturated vapor path by diode valves. Under heat  
4 addition, the pressure in the superheater increases to a  
5 pressure level much higher than that in the high-pressure  
6 saturated vapor line. Flow from the superheater is isolated by  
7 the use of the diode valve on the saturated vapor side and is  
8 released by the use of the control valves. When the pressure in  
9 the pulse oscillating superheater reaches a predetermined  
10 valve, the control valve is opened exposing the high-pressure  
11 superheated vapor to the superheated vapor path that leads to  
12 the turbine. The high-pressure superheated vapor travels  
13 through the superheated vapor path to a turbine where power can  
14 then be efficiently extracted. The flow from the turbine enters  
15 the condenser, such as a radiator, where the low-pressure  
16 saturated vapor condenses into liquid. The unidirectional flow  
17 around the system is maintained but operating with  
18 significantly increased pressure ranges, temperature ranges,  
19 and power levels with improved efficiencies over simple  
20 capillary pumped devices. The liquid pump and liquid preheater  
21 are preferably added to further increase the operating range  
22 and efficiency of the system.

23  
24 A working fluid, such as ammonia or water obtains a liquid  
25 phase and a vapor phase in the two-phase power generation  
26 system. Starting at the saturated liquid path, high-pressure,  
27 high-temperature saturated liquid moving along a high-pressure,  
28 high-temperature saturated liquid path to the evaporator being



1 a capillary device having a capillary wick within a wick  
2 container. The evaporator may be, for example, an evaporator  
3 from a conventional loop heat pipe or a conventional capillary  
4 pumped loop. Forced heat into the evaporator serves to drive  
5 the capillary device. This high-pressure, high-temperature,  
6 saturated liquid is pushed into the capillary wick under  
7 pressure. The capillary wick provides the separation between  
8 the high-pressure saturated vapor and the high-pressure, high-  
9 temperature saturated liquid. Flow through the capillary wick  
10 is achieved because the working liquid wets the capillary wick  
11 as fluid molecules are attracted to the capillary wick more  
12 than to each other to draw the working fluid through the  
13 capillary wick. The fluid is also pushed through the capillary  
14 wick from the pressure generated at the saturated vapor side of  
15 the capillary wick, in the superheater and from the liquid  
16 pump. Heat from the capillary heat source is fed into the  
17 capillary wick that is further connected to the capillary  
18 evaporator that is in turn connected to a high-pressure  
19 saturated vapor path in which the working fluid is a saturated  
20 vapor. Vaporization increases the volume and pressure of the  
21 working fluid on the heated output side of the capillary wick.  
22 The vapor pressure pushes the working fluid as high-pressure  
23 saturated vapor forward through the high-pressure saturated  
24 vapor path towards the vapor accumulator and superheater. Flow  
25 backwards toward the saturated liquid path is blocked because  
26 the pores in the capillary wick are so small that the working  
27 fluid forms a meniscus in the capillaries. The meniscus serves  
28 as a barrier to the high-pressure saturated vapor. The pressure

1 differential on opposing sides of the capillary wick is used to  
2 provide flow through the accumulator to the superheater.

3

4       The high-pressure saturated vapor path flow is connected  
5 to a superheater. The high-pressure saturated vapor is heated  
6 by the superheater connected to a superheated vapor path that  
7 connects to a turbine to produce power as work out. The vapor  
8 flows from the superheater through the turbine, extracting work  
9 and simultaneously lowering the pressure of the working fluid  
10 flow that reaches the low-pressure saturated vapor point. The  
11 superheater is a heat exchanger that may interface with the  
12 capillary heat source and preheater heat source in any  
13 combination or all heat sources can be separate. Heat sources  
14 can be radioisotope, active nuclear, and or solar. The heat  
15 source for the capillary device and liquid preheater is at a  
16 lower temperature than the heat source for the superheater. The  
17 heat source can include a thermal energy storage material such  
18 as a salt or liquid metal that having a single phase or  
19 multiple phases for providing heat during time of solar shade  
20 as when in a low earth orbit, while the superheater heat source  
21 is also a solar heat source for providing heat during times of  
22 solar illumination. The heat source for the capillary device  
23 and liquid preheater can be waste heat from a spacecraft or  
24 waste heat rejected from another power system. The superheater  
25 is preferably tubes with respective input diode valves and  
26 output control valves. The working fluid flows through the  
27 diode valves, into tubes that may hav several serpentine  
28 bends, and then through the control valves in an oscillating

1 manner having staggered releases of superh ated vapor. The  
2 working fluid flow exits the superheater as a superheated  
3 vapor. The superheat d vapor flows through the superheated  
4 vapor flow path. The superheater adds heat to the working fluid  
5 that ensures that no condensed liquid droplets enter the  
6 turbine. Superheated vapor can prevent erosion of the turbine.  
7 The superheated vapor path provides superheated vapor to drive  
8 the turbine. The superheated vapor flow drops in pressure as it  
9 flows through the turbine where energy is extracted in the form  
10 of mechanical energy, through a shaft, not shown. This  
11 mechanical energy can be used to perform useful work such as  
12 work out for turning a generator to generate electrical power.  
13 The low-pressure saturated vapor flow path is connected to the  
14 low-pressure side of the turbine. The working fluid can be  
15 nearly at saturation, slightly superheated or at a quality of  
16 typically above 90% as it flows through the low-pressure  
17 saturated vapor path out of the turbine. The low-pressure  
18 saturated vapor path is connected to the condenser. The working  
19 fluid flow will then enter the condenser from the low-pressure  
20 saturated vapor path. In the condenser, the working fluid will  
21 change phase, from a low-pressure vapor to a low-pressure  
22 liquid. Heat will be transferred out to an external sink, such  
23 as a radiator, in the environment as heat out. As the working  
24 fluid flow passes through the condenser, the working fluid  
25 undergoes a phase change from vapor to liquid. The condenser  
26 can be a tube through which working fluid flow passes using  
27 several serpentine bends. This tube is exposed to a cold heat  
28 sink, such as outer space. The exit of th condenser is

1 connected to the low-pressure saturated liquid path. The  
2 working fluid flows from the condenser through the low-pressure  
3 saturated liquid path to an optional liquid pump. The liquid  
4 pump increases the pressure of the flow. The flow exits the  
5 pump through the high-pressure and low-temperature liquid path.  
6 The flow then enters an optional liquid preheater. The liquid  
7 pump and liquid preheater can be used to extend the performance  
8 envelop of the power cycle. This allows for a broad choice of  
9 operating fluids, power levels and boundary condition  
10 temperatures. The liquid preheater adds heat to the flow to  
11 increase the liquid temperature. The preheater can provide heat  
12 from the same heat source as the superheater heat source or the  
13 capillary heat source or the preheater can be heated from an  
14 independent heat source. The flow then enters the high-pressure  
15 and high-temperature saturated liquid path that is connected to  
16 the capillary wick. The cycle is repeated as the working fluid  
17 passes through the system for power generation.

18  
19 Referring to the Figures, and particularly to Figure 2, the  
20 thermocycle can also be described with respect to fluid  
21 entropy. The working fluid preferably enters the capillary wick  
22 at a high-pressure high-temperature saturated liquid point. The  
23 liquid at the high-pressure high-temperature saturated liquid  
24 point and the vapor at the high-pressure saturated vapor point  
25 are completely separated during the heat addition to the  
26 capillary wick. During heat addition, saturated liquid changes  
27 directly to saturated vapor crossing the capillary interface  
28 jump. Crossing the capillary interface causes the working fluid

1 to go directly from a saturated liquid to a saturated vapor  
2 without a mixture of vapor and liquid occurring during the heat  
3 addition process. That is, the capillary interface jump on the  
4 temperature and entropy graph of Figure 2 mirrors the physics  
5 at the liquid vapor interface of the capillary wick, where  
6 lower-pressure liquid is physically in contact but separated  
7 from higher-pressure vapor. That is, at the vapor-liquid  
8 interface the liquid and vapor are in contact but separated.  
9 After heat addition, the working fluid is at the high-pressure  
10 saturated vapor point. The vapor is accumulated by the vapor  
11 accumulator, during operation the accumulator dampens pressure  
12 oscillations to the evaporator occurring from flow entering the  
13 superheater in pulses. As flow leaves the high pressure  
14 saturated vapor line and enters the superheater, flowing  
15 through the diode valves, pressure in the high-pressure  
16 saturated vapor line will momentarily drop. If this pressure  
17 drop is large enough, it could affect the operation of the  
18 evaporator. The accumulator effectively increases the overall  
19 volume of the high pressure saturated vapor available to the  
20 superheater and can be sized so that pressure oscillations are  
21 minimized. The accumulated high-pressure saturated vapor from  
22 the vapor accumulator flows into the superheater for  
23 superheating to a superheated vapor point. The superheated  
24 vapor at the superheated vapor point is passed through the  
25 turbine that cools the superheated vapor to low-pressure  
26 saturated vapor at the low-pressure saturated vapor point. The  
27 low-pressure saturated vapor is passed through the condenser  
28 that changes the phase by a condenser phase change of the

1 working fluid to a low-pressure saturated liquid at the low-  
2 pressure saturated liquid point. The low-pressure saturated  
3 liquid is pressurized to a subcooled state by the liquid pump  
4 and becomes a high-pressure low-temperature subcooled liquid at  
5 a high-pressure low-temperature subcooled liquid point. The  
6 high-pressure subcooled liquid is then heated by the preheater  
7 changing the flow into the high-pressure high-temperature  
8 saturated liquid at the high-pressure high-temperature  
9 saturated liquid point where the working fluid enters the  
10 capillary wick, to complete the entropy cycle.

11

12 Referring to Figures, and particularly to the superheater,  
13 the superheater is divided into parallel stages each having a  
14 respective diode valve, chamber, and control valve. The  
15 superheater can have as many stages as desired. For simplicity,  
16 a two-stage superheater is described having chambers A and B.  
17 Both chambers A and B are subjected to continuous steady state  
18 heat input from the superheater heat source. At time equal to  
19 zero, that is,  $T=0$ , the pressure in the superheater stage A is  
20 low at  $P_{low}$ , the pressure in the superheater stage B is high at  
21  $P_{high}$ . At time  $T=0$ , the high-pressure saturated vapor flows into  
22 chamber A and the control valve A is closed. The control valve  
23 B for chamber B is then opened. When opened, high-pressure  
24 superheated vapor is injected by pressure into the superheated  
25 vapor flow path toward the turbine. At time equal to one, that  
26 is,  $T=1$ , the pressure of chamber A reaches a pressure equal to  
27 the pressure of the high pressure saturated vapor line pressure  
28  $P_{equal}$ . At time  $T=1$  flow into chamber A stops, as the control

1 valve B for chamber B closes, and the pressure in chamber B is  
2 now at  $P_{low}$ , and the saturated vapor flow begins to enter  
3 chamber B. At time  $T=2$ , chamber A reaches the high-pressure  
4  $P_{high}$ , and the control valve A is opened exposing high-pressure  
5 superheated vapor to the superheated vapor path toward the  
6 turbine. Flow again travels through the superheated vapor path  
7 toward the turbine. When the pressure in chamber B reaches  
8  $P_{equal}$  where superheated vapor flow in stops and the control  
9 valve B remains closed. At time three  $T=3$ , the two chambers A  
10 and B reach the same pressure as at time  $T=0$ , to complete the  
11 staggered pulsed cycling of the superheater. It should now be  
12 apparent that the flow from the superheater is staggered in  
13 pulse from the plurality of the chambers. It should further be  
14 apparent that other types of multiple stage superheaters could  
15 be used, such as inline superheaters using cascaded chambers  
16 operating in incremental predetermined temperature valves, but  
17 still having pulsed injection of incremental amounts of  
18 superheated vapor toward the turbine.

19  
20 The high-pressure saturated vapor path from the capillary  
21 device is preferably connected to the vapor accumulator.  
22 Saturated vapor flows out of the vapor accumulator to the  
23 superheater. The vapor accumulator is an empty pressure vessel  
24 so that vapor can enter the superheater in mass flow pulses.  
25 The function of the vapor accumulator is to isolate the  
26 capillary evaporator from vapor mass flow pulses caused by the  
27 vapor flow stopping and starting at the superheater entrance of  
28 the unidirectional diode valves. These mass flow pulses could

1 have an adverse effect on the ability of the capillary  
2 evaporator to maintain separation of vapor and liquid. These  
3 pulses could also cause a reduction in the temperature of the  
4 saturated vapor exiting the capillary evaporator. The volume of  
5 the vapor accumulator is such that vapor mass flow pulses  
6 induced at the superheater entrance will be dampened a  
7 sufficient amount so that there will be no adverse effect from  
8 these pulses on the capillary evaporator.

9  
10 The saturated low-pressure liquid path is connected to a  
11 liquid pump. Liquid flows out of the liquid pump through the  
12 subcooled high-pressure low-temperature liquid path. The liquid  
13 pump can be a conventional terrestrial two-phase power cycle  
14 pump and be capable of increasing the pressure of the liquid by  
15 several hundred pounds per square inch. The liquid pump  
16 requires electric power input. A liquid pump in cycle is  
17 operated to increase the pressure of the working fluid liquid  
18 prior to entering the capillary evaporator. By increasing the  
19 pressure before entering the capillary evaporator, the pressure  
20 difference between the saturated high-pressure high-temperature  
21 liquid entering the evaporator and the high-pressure saturated  
22 vapor leaving the evaporator can be minimized while the  
23 saturated low-pressure liquid pressure in the condenser is  
24 chosen for optimum cycle efficiency. Using a liquid pump allows  
25 for increased cycle efficiency by enabling a lower operating  
26 temperature in the condenser.



1       The liquid preheat r is connected to the subcooled high-  
2 pressure low-temperature subcooled liquid path from the liquid  
3 pump. Liquid flows out of the liquid preheater into the  
4 saturated high-pressure high-temperature saturated liquid path  
5 towards the capillary wick. The liquid preheater can be a  
6 hollow tube that interfaces with a preheater heat source to  
7 allow for heat addition. The preheater heat source is attached  
8 to the liquid preheater tube. The heat source can be waste heat  
9 from a spacecraft, solar energy, or nuclear energy. The heat  
10 source for the liquid preheater can be the same as or separate  
11 from the heat source for the capillary evaporator or the  
12 superheater.

13  
14       With a liquid pump incorporated into the power cycle, low  
15 operating temperatures, just above the freezing point of the  
16 working fluid, are possible in the condenser. After this cold  
17 fluid from the condenser passes through the liquid pump, it is  
18 significantly subcooled. If this fluid were returned directly  
19 to the evaporator without passing through the liquid preheater,  
20 a significant amount of additional heat would need to be added  
21 through the evaporator, beyond that required only for  
22 evaporation of the fluid. This significant amount of added heat  
23 may adversely affect the performance of the capillary  
24 evaporator by requiring a significantly higher temperature for  
25 heat input to the evaporator. Adding the liquid preheater to  
26 the cycle allows for the liquid to be preheated prior to  
27 entering the evaporator which enables the evaporator to operate

28

1 at high efficiency while the power cycle operates over an  
2 extended temperature range.

3

4 The thermodynamic power system is well suited for a  
5 variety of space applications such as a primary power system  
6 using a radioisotope, active nuclear, waste heat, and/or solar  
7 energy as a heat source. These heat sources are useful for  
8 heating the liquid preheater, the capillary wick and the pulse  
9 superheater and driving the working fluid flow for increased  
10 power efficiency and lifetime operation. The power system is  
11 well suited for space receiving heat from a heat source to  
12 produce useful mechanical energy. The two-phase thermodynamic  
13 power cycle provides improved efficiency of over 30% while  
14 operating at a maximum temperature of 637.4K. The system yields  
15 a power converter that is efficient while operating at  
16 relatively low maximum temperatures. Also, because the heat  
17 addition process occurs at varying temperatures, low-grade  
18 waste can be used to supplement the energy heat source  
19 requirements. Those skilled in the art can make enhancements,  
20 improvements, and modifications to the invention, and these  
21 enhancements, improvements, and modifications may nonetheless  
22 fall within the spirit and scope of the following claims.

23

24

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